

17-5358 02/23/2019 11:16 AM 11/18/2019 11:16 AM 11/18/2019 11:16 AM

August 25, 1971

N72-23053

63/03      27167      Unclas

## Contract Summary Report

Contract NAS 9-11033, Data Item No. 36

Prepared for

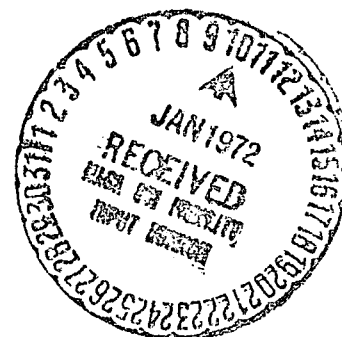
National Aeronautics and Space Administration  
Manned Spacecraft Center  
R and D Procurement Branch  
Houston, Texas 77058

## DIRECT ENERGY CONVERSION PROGRAMS

AIRCRAFT EQUIPMENT DIVISION  
LYNN, MASSACHUSETTS

GENERAL  ELECTRIC

Reproduced by  
**NATIONAL TECHNICAL  
INFORMATION SERVICE**  
U S Department of Commerce  
Springfield VA 22151



23

TABLE OF CONTENTS

		<u>Page</u>
1.0	Objective	1
2.0	Approach	1
	2.1 General	1
	2.2 Technical	2
	2.3 Program	3
3.0	Accomplishments	4
	3.1 Conceptual Design	4
	3.2 Component Assembly and Test	4
	3.2.1 Small Stack Tests	4
	3.2.2 Ancillary Component Tests	7
	3.2.3 Electronic Components	8
	3.2.4 Prehumidification Feasibility Tests	8
	3.3 Technology Advancement	9
	3.4 Phase B Contractors Liaison	9
	3.5 Complementary Engineering	10
4.0	Significant Achievements	10
5.0	Recommendations	10



## 1.0 Objective

The objective of this program was to advance the technology for a cost-effective hydrogen/oxygen fuel cell system for future manned spacecraft. The evaluation of base line design concepts and the development of product improvements in the areas of life, power, specific weight and volume, versatility of operation, field maintenance and thermal control were to be evaluated from the material and component level through the fabrication and test of an engineering model of the fuel cell system. The program was to be accomplished in a 13 month period (July 1970 - August 1971).

## 2.0 Approach

### 2.1 General

The approach for the program was to pursue three basic tasks with parallel efforts. Task I consisted of defining a base line design utilizing concepts representing low risk and based on significant prior experience. The fabrication and testing of materials and components of the base line configuration was the approach used to identify and resolve engineering problems.

Task II was focused on the identification and evaluation of concepts which would represent a significant extension of base line capability in the areas of life, power, specific weight and volume, versatility of operation, field maintenance capability and thermal control while still avoiding high technical risk approaches. Those concepts which offered significant improvements were evaluated at the component or subsystem level and introduced as a modification to the base line design where the time phasing with Task I permitted.

Task III consisted of liaison and coordination with the Space Shuttle Phase B Prime Contractors to provide for two-way information exchange in order to perform cost effective system trade-off studies to establish base line fuel cell system requirements.

Management Tasks were implemented for the program planning, resources control, schedule control, NASA liaison and coordination, configuration management and documentation.

Complementary Engineering Tasks, as defined in supporting exhibits to the Statement of Work, were implemented in the areas of Reliability, Quality Assurance, System Safety and Mass Properties Control for the identification and study of factors pertinent to these disciplines which would affect the evaluation of the base line design.

At the time this program began, a second generation of cell assembly configuration beyond the designs used in the Gemini and Biosatellite spacecraft applications had been developed under Air Force Contract F33615-67-C-1830. This design represented a considerable advancement in weight, power density and temperature capabilities over the first generation hardware. The cell assembly consisted of two solid polymer electrolyte (SPE) cells of 0.35 ft<sup>2</sup> active area each, bonded to a common cooling cartridge such that two anodes faced the cooling cartridge. The current was carried by gold screens embedded in the electrodes to the edge of the cell and by bus bars and external tabs allowing the back-to-back cells to be connected in either series or parallel. Figure 1 shows a cutaway view of a cell assembly and Figure 2 shows a cross-section of the back-to-back cell assembly. The SPE was the "R" series of polymer developed by duPont which is capable of long invariant life performance as demonstrated by laboratory testing and the Biosatellite spacecraft program. Additional cell developments had been demonstrated in laboratory hardware that represented performance and cost advantages. The following design modifications to the back-to-back cell assembly configuration were incorporated into the initial base line design:

- a) The "R" series of SPE manufactured as a single-ply extrusion vs. the earlier method of laminating two plies of polymer which had been skived from a cast block.
- b) A peroxide scavenging catalyst in the SPE (platinizing).
- c) Reductions in catalyst loadings for both anode and cathode electrodes.
- d) A porous Teflon wetproofing film for the cathode.
- e) Elimination of the internal gold bus bars and compensated for by an increase in the electrode screen cross-sectional area to achieve an equivalent electrical resistance. The thickness of the screen strand remained at .003 inch and the width was increased from .005 to .007 inch.
- f) Addition of a primer to the bonding system.
- g) External bus bar connections for electrically paralleling cells within a cell assembly.

A sizing study was performed based on cell performance observed during the AFAPL program and laboratory cell test data. The fuel cell module was designed to produce 5 KW of steady state power at a reactant inlet pressure of 20 psia for compatibility with operation from a propulsion tank supply. This study resulted in the selection of a base line module configuration of two stacks of 40 cell assemblies to produce 5 KW above the minimum specified voltage of  $28 \pm 5\%$  VDC. The operating temperature of 150°F was selected for maximum performance at 20 psia and a conservative point for hardware life capabilities.



The design of the ancillary components for the fuel cell system was based on experience from the Gemini and Biosatellite spacecraft programs with the objective of using off-the-shelf and minimally modified components proven in other space vehicle applications. The fuel cell system was designed as a self-contained module with a minimum of vehicle interface requirements. Since the fail operational/fail safe criterion was being designed into the number of fuel cell modules selected for the vehicle, it was considered unnecessary to include any redundant elements within the module until such time as an actual reliability assessment could be made on all components as a result of test data.

### 2.3 Program

The Work Breakdown Structure and Major Milestone Chart for the effort as originally planned is shown on Table I. The tasks and subtasks were defined and scheduled following the Statement of Work format. The premature life test failures on small stack Buildups 1 and 2 occurred in November and December 1970, resulting in considerable additional failure analysis effort.

Because of the additional analysis effort caused by these failures, it was necessary to revise the program plan to concentrate the remaining contract funds and efforts in the key technology development areas. The original Program Plan was modified in January 1971. In order to make funding available for failure analysis and additional small stack testing, it was decided to fabricate EM-1 as a one stack module (40-cell assemblies) rather than two stacks and to eliminate the electromagnetic testing. Small stack Buildup 3 was originally planned as a 4-cell assembly unit to evaluate the developments evolved from the Task II efforts and this was reduced to a single-cell assembly unit. At the same time, development of electronic components such as the voltage regulator and the monitoring control unit was suspended since they represented a more available state-of-the-art technology. Some effort was also cut back in the Complementary Engineering areas of Reliability and Safety.

In March and April 1971, with the premature life test failures of small stack Buildups 4 and 5, an extensive failure mode parametric matrix evaluation was implemented. Thus, it was necessary to make further reductions in the originally planned work scope in order to fit the key efforts within the available funding. At this point the EM-1 test unit was completely eliminated from the program.

Contract Amendment No. 2S, dated 27 May 1971 terminated all work under the contract except for specific tasks listed below:

- a) Life test valves and regulators.
- b) Life cycle test coolant loop.
- c) Failure analysis and reports.
- d) Final program documentation.



A separate contract (NAS 9-11876) covering the time period from 3 May to 30 November 1971 funded the fabrication and life test of two small stacks (Buildups 101 and 102). The objective of this program is to demonstrate the effectiveness of the prehumidified reactants in Space Shuttle hardware.

### 3.0 Accomplishments

#### 3.1 Conceptual Design

A base line design was completed for a 5 KW fuel cell module, including detail drawings, component specifications, end item specifications and process control instructions. The module consists of two stacks of 40 cell assemblies each, sized to operate at propulsion tank pressures of 20 to 45 psia and on propulsion-grade reactants. The fuel cell module schematic shown on Figure 3 identifies the ancillary components that comprise the complete module. The module is designed with a self-contained Monitoring and Control Unit to completely and safely isolate it from the vehicle in the event of internal failure. Figure 3 also shows a typical fuel cell module outline and installation drawing. The ancillary components may be relocated in order to fit any particular installation. The performance capabilities of the fuel cell module are shown in Figure 4. The fuel cell module weight is 150 lb or 30 lb/KW.

#### 3.2 Component Assembly and Test

##### 3.2.1 Small Stack Tests

Small stacks (8 cells/4 cell assemblies) of Space Shuttle base line design cells were life tested to simulated mission power profiles and stop/start cycles. The first two small stack units (Buildups 1 and 2) fabricated to the same configuration failed at 807 and 897 hours, respectively.

Following the failure analysis efforts, a series of corrective actions was introduced into the fabrication of two additional small stack units (Buildups 4 and 5). The corrective actions incorporated were as follows:

- a) Increased water content of SPE from 28 to 38 wt %.
- b) Divided hydrogen flow into eight compartments, where the previous configuration allowed all the hydrogen flow to enter the cell over a concentrated area.
- c) Increased anode catalyst loading from 4 to 32 mg/cm<sup>2</sup>.
- d) Moved the bonding interface away from the reactant inlet area.
- e) Moved the oxygen inlet tube behind the product water wick.
- f) Prehumidified the oxygen in the test facilities on Buildup 5.



g) Modified the stop/start procedures and the activation procedures.

The two units experienced failures at 450 and 650 hours, respectively.

The single-cell test unit (Buildup 3) was fabricated to the same configuration as Buildup 1 and 2 except the SPE membrane water content was increased from 28 to 38% as a result of the laboratory evaluations in Task II. This unit was removed from test after 408 hours to modify the oxygen side in order to correct the condition presumed to be the cause of failure in Buildup 2. The unit was returned to test redesignated as Buildup 3A and continued to operate satisfactorily through 2000 hours. Attempts to continue the testing beyond that point were terminated at 2031 hours when a slight leak developed in a bonded area under the gold bus bars. Thus, it was demonstrated that flight-type hardware had the inherent life capability of at least 2000 hours.

In parallel with the fabrication and life testing of the Space Shuttle small stack units, there were two GE-funded test units fabricated into gasketed boilerplate hardware with the same active cell areas and the same membrane and electrode configurations. These were designed as ground power units and differ from space-type units in weight and water removal methods. One of these Advanced Fuel Cell units (AFC 6) was a four cell stack which was operated for 3000 hours to the same temperatures (150°F) and load profiles (60, 135 ASF) as the Space Shuttle hardware. Then the operating conditions were increased to 180°F and double the load profile (120, 270 ASF). AFC 6 has operated for an additional 2000 hours at these conditions and is still on test. The other test unit of the same boilerplate construction is a single cell unit (AFC 1) and has been on a standby test at a trickle load of 1 ASF for more than 8800 hours at 150°F and is still operating.

A comparison of the hardware configuration of the Advanced Fuel Cell units (AFC) and the Space Shuttle buildups is shown in Figure 5, along with a cross-section of the AFC hardware. The membrane and electrode configuration of the AFC hardware is the same as configurations used in the Space Shuttle buildups. The key difference is in the conditioning of the reactants in the AFC hardware before reaching the active area of the cells as shown in Figure 2. In the AFC hardware the oxygen is humidified by bubbling through a head of water maintained in the cathode compartment. The hydrogen is introduced at a point below the water level on the opposite side of the SPE. The water head resupplies water to the SPE in the area where water is being removed to saturate the incoming hydrogen.

All of the failures in the Space Shuttle cell assemblies can be categorized by the following observations:

- a) All cell failures were in the dry gas inlet areas of the cell.
- b) All cells were delaminated (blistered) at the dry gas inlet area of the cells.
- c) Delaminated areas show oxidative degradation of the polymer, indicating breakage of polymer chains.



- d) Physical properties of the polymer in the delaminated areas have been reduced.
- e) Cell performance is stable and invariant to within minutes of the failure.
- f) The automatic monitoring control facilities safely isolated the failures in every case.

An extensive series of failure simulation tests and a matrix of tests to evaluate parameters influencing the degree of delamination and production of HF in product water led to the following conclusions:

- a) Delaminations could not be reproduced outside of operating hardware.
- b) The dominant parameter affecting both delamination and HF production is the degree of humidification of the reactant gases entering the active area of the cell.
- c) A secondary effect noted was that platinized membranes result in more delamination and HF production than non-platinized membranes.
- d) Removal of the cathode catalyst at the reactant inlet areas eliminates delaminations in that area.

The data accumulated plus consultation with various polymer chemists led to the following postulated failure mechanism:

- a) Dry reactant gases entering the cell remove water from the SPE, creating stresses within the polymer as it tends to shrink.
- b) Stress/strain applied to the polymer causes some breakage of the  $\text{-(CF}_2\text{ - CF}_2\text{)-}$  bonds in the polymer chains.
- c) Hydrogen peroxide produced at the cathode during operation migrates to the weak or broken links in the chain and initiates a free radical attack leaving  $\text{-(CFH and CFOH)-}$  which further degrade to HF and  $\text{CO}_2$ .
- d) The principle degradation occurs at the center of the SPE, resulting in delamination due either to a concentration of stress at this point caused by the drying and shrinking of one side or by inherent strains or partially broken chains in the center as a result of membrane fabrication.
- e) The weakened and delaminated membrane ultimately develops stress cracks from the continual tensile forces induced by drying of the membrane.





Accomplishments in this area were the identification of the life limiting problem encountered in the Space Shuttle hardware configuration and the demonstration of a long life capability for the membrane and electrode assembly of the Space Shuttle size of cell tested in the boilerplate gasketed hardware. The ability to operate the SPE fuel cell on propulsion-grade reactants and at propulsion tank pressures was demonstrated. All of the small stack buildup testing was done without hydrogen purging during the mission operation and the periodic oxygen purging was accomplished with 1% of reactant consumption.

The average single cell performance demonstrated in the small stack buildups was as shown in Figure 6. This level is approximately 30 millivolts lower than the performance predicted for the Space Shuttle hardware. Investigation as to the cause for this parallel downward shift of the polarization has indicated a contamination of the cathode electrode from constituents of the bonding adhesive material. The loss has been consistent between units and stable throughout the life tests. Solutions to this problem were deferred to later follow-on phases of the technology development. The performance of the AFC 6 unit also given in Figure 6 shows the demonstration of performance capability without the contamination loss and a still further improvement resulting from a reduction of internal resistance loss in the cell assembly.

### 3.2.2 Ancillary Component Tests

The ancillary components for a fuel cell module as shown on the pneumatic schematic of Figure 3 were life tested in three simulated loops as follows:

Coolant loop components - operated 2500 hours at 150°F

- . Circulating Pump
- . Thermal Bypass Valve
- . Heat Exchanger
- . Coolant Accumulator
- .  $\Delta P$  Transducer

Hydrogen loop components - operated 2000 hours at 150°F

- . Reactant Regulator
- . Purge Valve
- . Inlet Latching Valve
- . Check Valve
- .  $\Delta P$  Transducer

Oxygen and product water loop components - operated 2000 hours at 150°F.

- . Water Pressure Regulator
- . Purge Valve
- . Inlet Latching Valve
- . Water Valve
- . Check Valve
- .  $\Delta P$  Transducer



The only problems encountered in the ancillary component life tests were a bellows failure in the water pressure regulator after 250 hours of test and a false indication from the position indicating switch on the oxygen inlet latching solenoid after 1800 hours. The bellows failure was caused by a small hole near the outer edge of a convolution resulting from corrosion in a small area from the oxygen side of the bellows. Improved methods for providing corrosion protection to the stainless steel bellows are being investigated. The switch problem on the latching solenoid valve did not impair the function of the valve. A false position signal resulted when power was applied to the solenoid causing both position signal lights to be energized. The problem has been eliminated by reworking the valve stem to remove a tolerance buildup condition.

### 3.2.3 Electronic Components

A voltage regulator breadboard circuit was fabricated and subjected to a preliminary evaluation before the effort was terminated by lack of funding. The step-down regulator was designed for 5 KW of power at 28 VDC. The preliminary evaluation indicated a regulation of  $28 \pm 1\%$  VDC at conversion efficiencies of 93 to 95%.

Breadboard circuits of the subcomponents to the Monitoring and Control Unit were also fabricated and subjected to a preliminary evaluation before the effort was terminated by lack of funding. Included was an automatic purge control based on amp-hours of operation and logic circuitry to sense module failure for activation of the valves and contactors to completely shutdown and isolate the module from the rest of the system. Breadboard electronic components that were life tested in conjunction with the ancillary components were the inverter for the pump motor and the pressure transducer signal amplifiers and comparators to signal out-of-tolerance  $\Delta P$ 's.

### 3.2.4 Prehumidification Feasibility Tests

A concept for prehumidifying the reactants before entry into the stack assembly was demonstrated in breadboard hardware. The design approach was to use an SPE without catalyst as a liquid/gas separator with the product water filling one side of a chamber divided by the SPE and using the exit coolant to provide the heat of vaporization to condition the temperature of the inlet reactants. Figure 7 shows a schematic view of this design concept. The breadboard models of the concept were tested for 900 hours, saturating both hydrogen and oxygen to cell inlet temperatures. Design data on water transport and gas flow rates were obtained during these tests. Thus the feasibility of prehumidifying the reactants was demonstrated on a design concept that requires no external supplies or power consumption. The prehumidifiers can be placed inside the module container, thereby eliminating any interface problems.



### 3.3 Technology Advancement

A parallel task to the design and development of the base line configuration was the exploitation of potential product improvements in the areas of weight, performance, reliability and cost effectiveness. This task was primarily a laboratory effort and produced the following results:

- a) Determined that the life capability of the SPE could be increased by changing the water content from 28 to 38% by weight. The laboratory testing indicated a life improvement factor of six times using accelerated conditions for relative evaluations.
- b) Bonding techniques and a primer for surface pretreatment were developed that significantly increased the bond strength with life aging. Satisfactory bond life was demonstrated for 2000 hours.
- c) Wicking and water separator materials were evaluated, resulting in the conclusion that the dacron wicks and the porous glass separator selected for the base line design are satisfactory for 2000 hours of fuel cell operation. Market surveys for improved materials revealed nothing better available at this time.
- d) Materials for cell assembly construction such as niobium, polysulfone, silicone rubber and Teflon proved to be stable and compatible with the fuel cell operating environments.

### 3.4 Phase B Contractors Liaison

Seven liaison meetings were held with McDonnell Douglas Aircraft Corporation and North American Rockwell Corporation along with the NASA Manned Spacecraft Center coordinator in order to maintain a two-way information exchange relative to the development of the base line designs and interface requirements for the Space Shuttle power supply. Trade-off study data in the following areas was provided to the prime contractors:

- Reactant purity and pressure.
- Voltage regulation.
- Voltage level.
- Module packaging.
- Program costs vs. life.
- Module redundancy.
- Warmup method.
- Module sizing vs. peak loads.



### 3.5 Complementary Engineering

The objective of this task was to perform reliability and safety studies in order to optimize the fuel cell module design concept and to implement procedures for quality control in the manufacturing processes. A preliminary Failure Mode and Effects Analysis and a Hazards Analysis Report were issued.

During the development of the manufacturing processes, the necessary process control specifications, and operation check lists were also developed to insure consistency and quality of fabrication.

### 4.0 Significant Achievements

- a) Identified operational and configuration parameters affecting operating life.
- b) Demonstrated capability of the SPE membrane and electrode assembly to operate for over 5000 hours of invariant performance with humidified reactants in AFC 6 units.
- c) Demonstrated the inherent capability of the flight weight Space Shuttle cell assembly configuration to operate for 2000 hours in Buildup 3.
- d) Demonstrated capability of operation on propulsion grade reactants.
- e) Demonstrated the elimination of H<sub>2</sub> purging and the reduction of O<sub>2</sub> purging to 1% of consumption.
- f) Demonstrated stop/start capabilities with relatively simple procedures.
- g) Demonstrated the safety of the automatic failure isolation concept.
- h) Demonstrated 2000 hour life capability of ancillary components.
- i) Designed a base-line fuel cell module weighing 30 lb/KW.

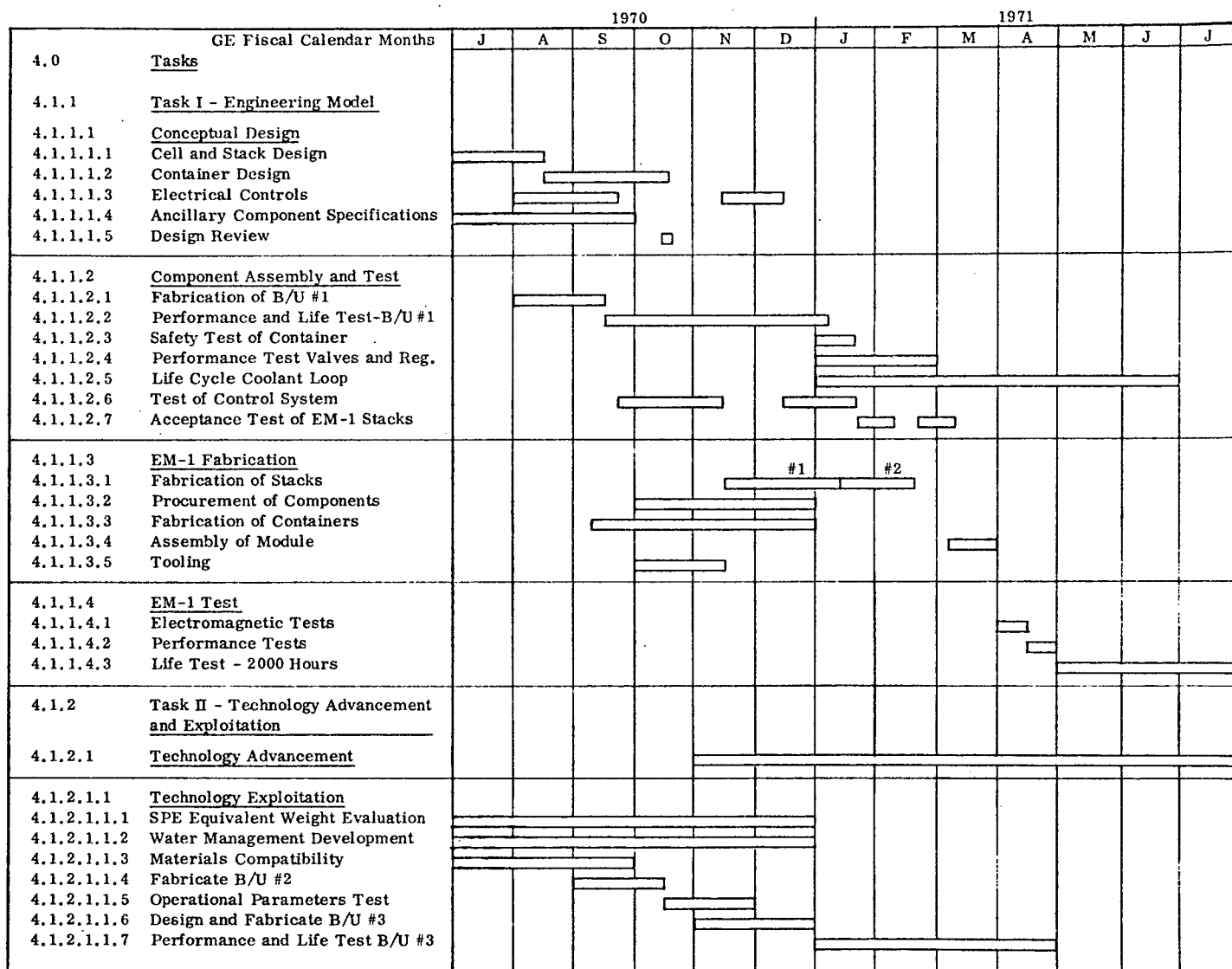
### 5.0 Recommendations

As a result of the technology evaluation and developments achieved under this contract it is recommended that the following additional efforts be undertaken to further the development of the solid polymer electrolyte type fuel cell for application to the Space Shuttle program and other future manned space flights:

1. Fabricate two additional small stack units (4 cell assemblies) and life test for 2000 hours.
  - (a) One of the units should be operated with both reactants prehumidified to saturation in the test facilities to provide a base line evaluation.
  - (b) The second unit should include a concept for internally recycling product water to the SPE opposite the hydrogen inlet area as a method of humidification for the incoming hydrogen. The oxygen should be prehumidified in the test facility.
  - (c) One of the two units should include thermocouples internal to the cell assemblies to obtain thermal data to compare end cell and middle cell conditions,  $\Delta T$ 's across the cells from coolant inlet to outlet and temperatures at the reactant inlets.
  - (d) One of the two units should have individual product water separation systems for the four cell assemblies to evaluate the distribution of HF production and possible correlations with cell performance or cell temperature.
2. Continue the matrix evaluations of configuration parameters affecting the HF production, delamination of the polymer and life of the SPE fuel cells.
3. Continue the laboratory evaluation of potential process changes to alleviate conditions shown to be contributing to the limitation of fuel cell operating life.
4. Pursue a program to identify the constituent in the bonding adhesive contributing to the observed performance loss and evaluate changes in formulation to the adhesive or alternate adhesives to eliminate the contaminant.
5. Evaluate the capabilities of cell and ancillary components to operate for satisfactory life at coolant temperatures of 180°F.
6. Fabricate and life test a full stack of cell assemblies (40 cell assemblies).
7. Develop and life test reactant prehumidifiers of flight-weight prototype configurations sized to support operation of a full stack.
8. Evaluate on the small stack unit (4 cell assemblies) the effects of activation methods, cyclic stop/start operations and higher current density operation.
9. Fabricate and life test a complete 5 KW fuel cell module.



Table I  
Major Milestone Chart  
Fuel Cell Technology Program



First Program Plan Revision

Second Program Plan Revision

Contract NAS 9-11876 for B/U's 101 and 102

Partial Contract Termination



Table I (Cont'd.)

		1970						1971						
Tasks (Continued)		J	A	S	O	N	D	J	F	M	A	M	J	J
4.1.3	Task III - Phase B Contracts Activities													
4.1.3.1	Liaison		◇	◇		◇	◇		◇	◇		◇	◇	
4.1.3.2	Supporting Technology			As Required										
4.1.3.3	Cost Effectiveness			As Required										
4.2	Management Tasks													
4.2.1	Overall Program Management			Continuous Activity										
4.2.2	Program Plan			Revise As Needed										
4.2.3	Task Support Plans and Schedules			Revise As Needed										
4.2.4	NASA Coordination				◇			◇			◇			◇
4.2.5	Configuration Management			Continuous Activity										
4.2.6	Resources Control Plan			Continuous Activity										
4.2.7	Documentation			Refer to Exhibit "C" - Table I										
4.3	Complementary Engineering													
4.3.1	Reliability and Quality Assurance													
4.3.1.1	Reliability Program Plan													
4.3.1.2	FMEA													
4.3.1.3	Trade-off Studies													
4.3.1.4	Reliability Analysis													
4.3.2	System Safety													
4.3.2.1	System Safety Plan													
4.3.2.2	Hazard Report													
4.3.2.3	Safety Test Failure Reports			As Required										
4.3.2.4	Safety Analysis Report													
4.3.3	Electromagnetic Interference EMI Plan			Continuous Activity										
4.3.4	Mass Properties Control			Continuous Activity										



# FOLDOUT FRAME

D

C

B

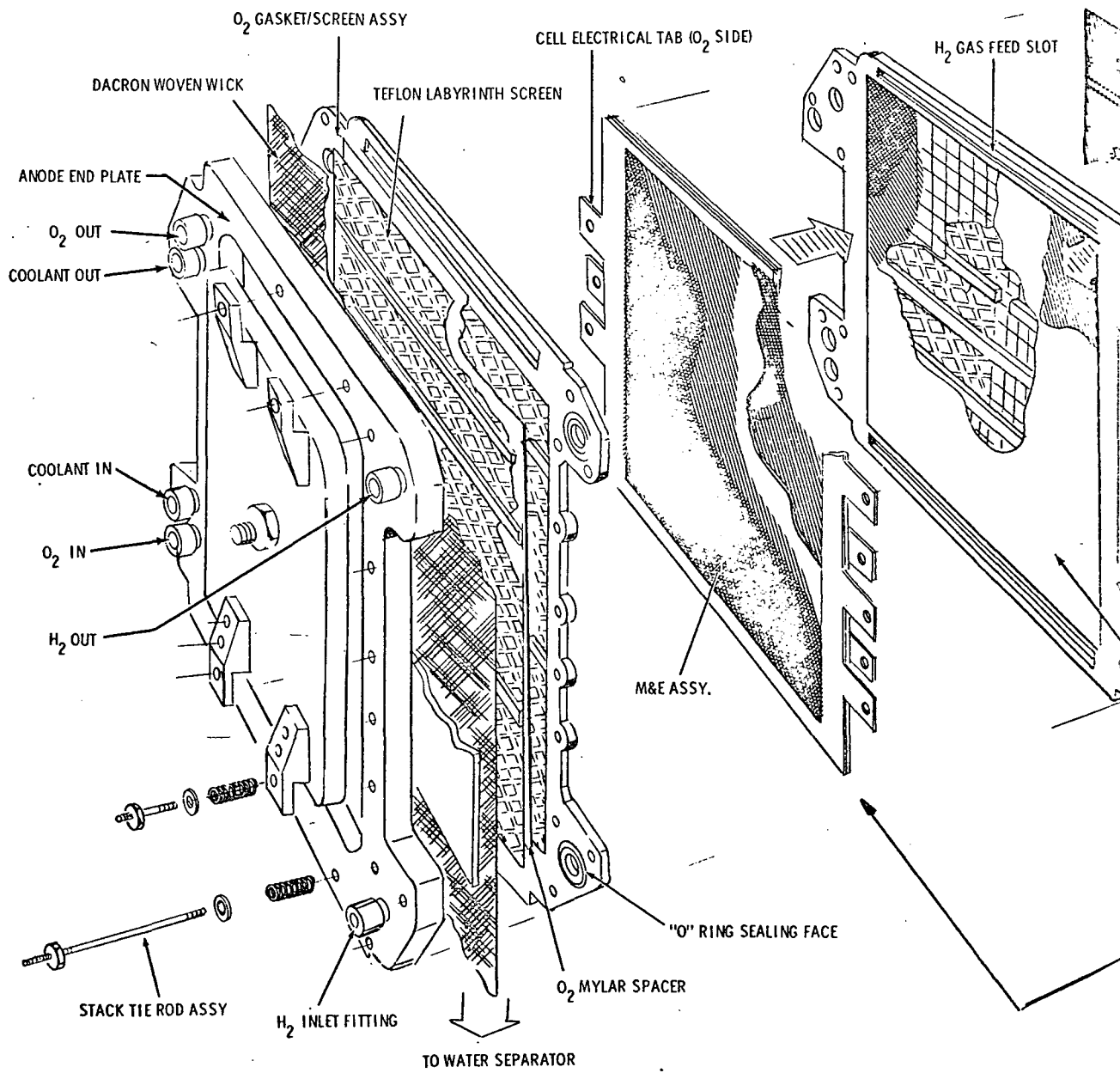
A

8

7

6

5



REPRODUCED FROM  
NATIONAL BUREAU OF STANDARDS

DC-322 (11-60)

8

7

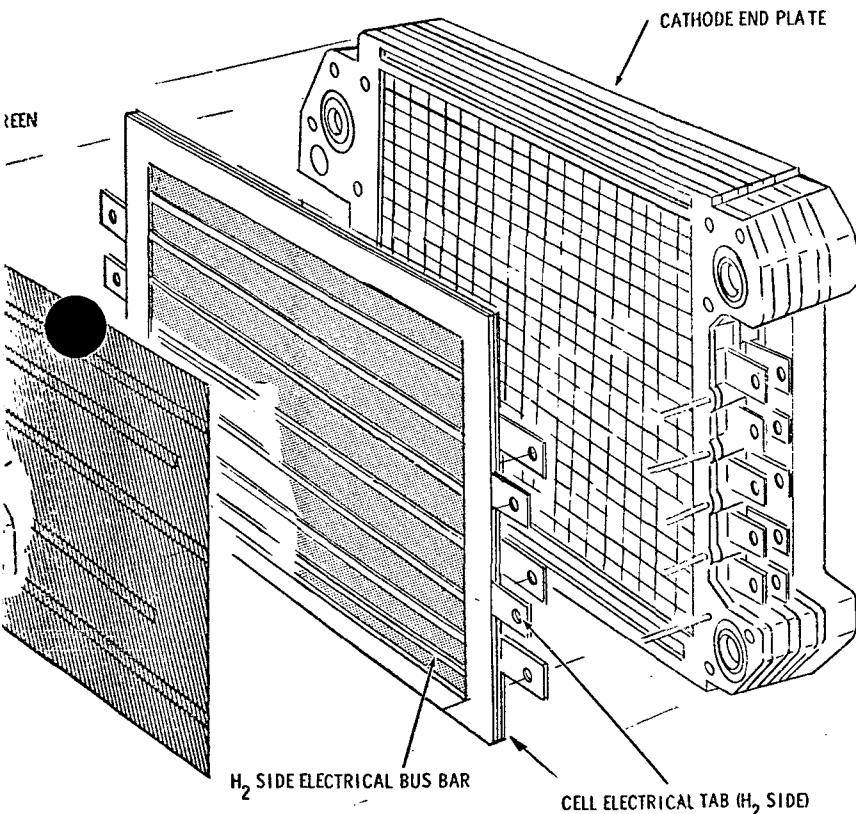
6

5



REVISIONS			
ZONE	LTR	DESCRIPTION	DATE

FOLDOUT FRAME



COOLANT CARTRIDGE

2 CELL MODULE

DWG TYPE ASSY-SKETCH			
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		GENERAL ELECTRIC DIRECT ENERGY CONVERSION OPERATION, LYNN, MASS., U.S.A.	
SIGNATURES	MO. DA. YR.	FUEL CELL STACK ASSY	
DRAWN 3.0 ADVANTAGES	4-4-70		
CHECKED			
ENGR. H. D. D'Amico	4/7/70		
MATL			
FOR G.E. USE ONLY			
SIMILAR TO			
L/O			
DR			
		SIZE D	CODE IDENT NO. 14736
		DWG NO. 1076527-720	
		SCALE	WT. CALC. ACTUAL
		SHEET	

Figure 1 14

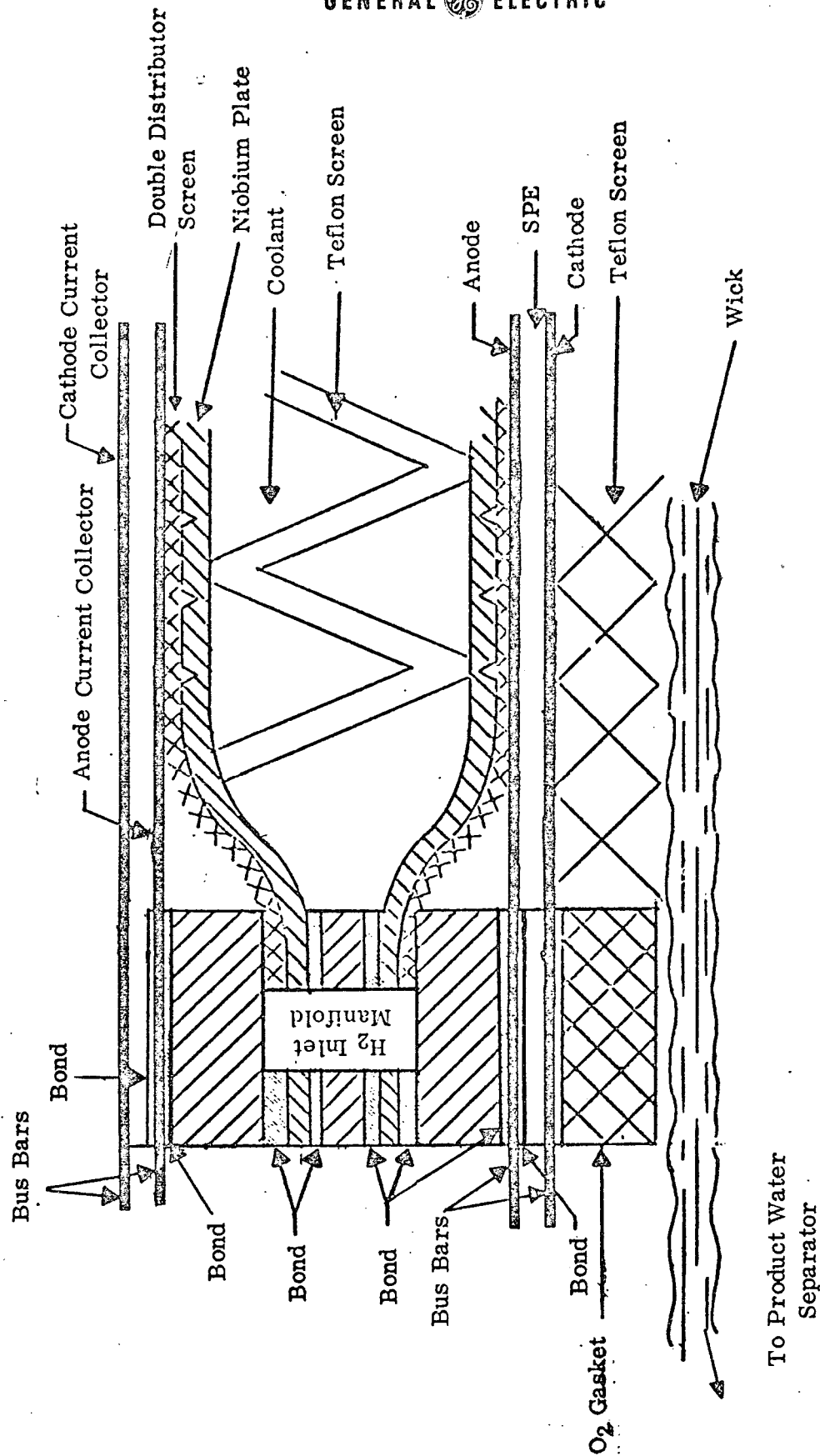
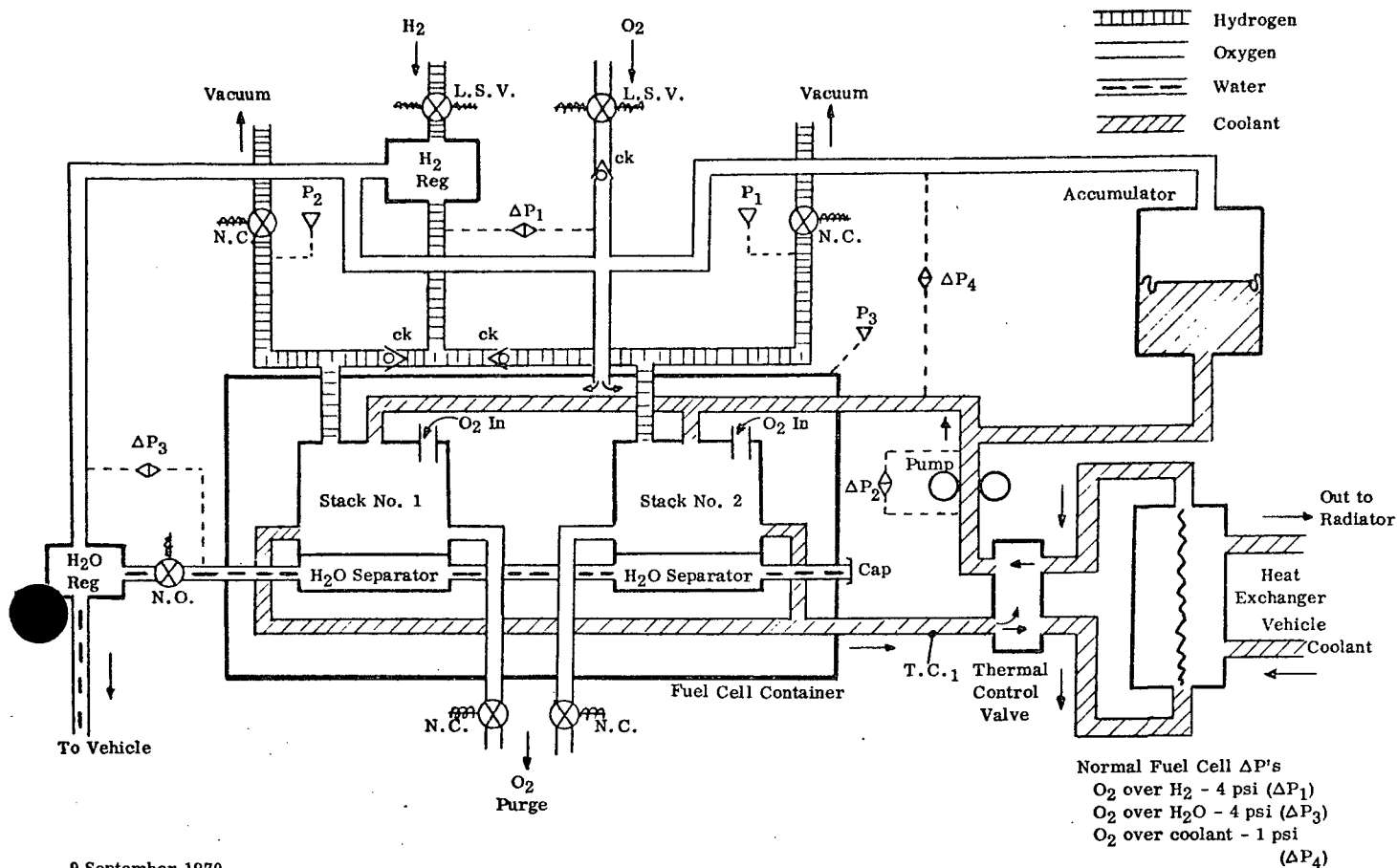
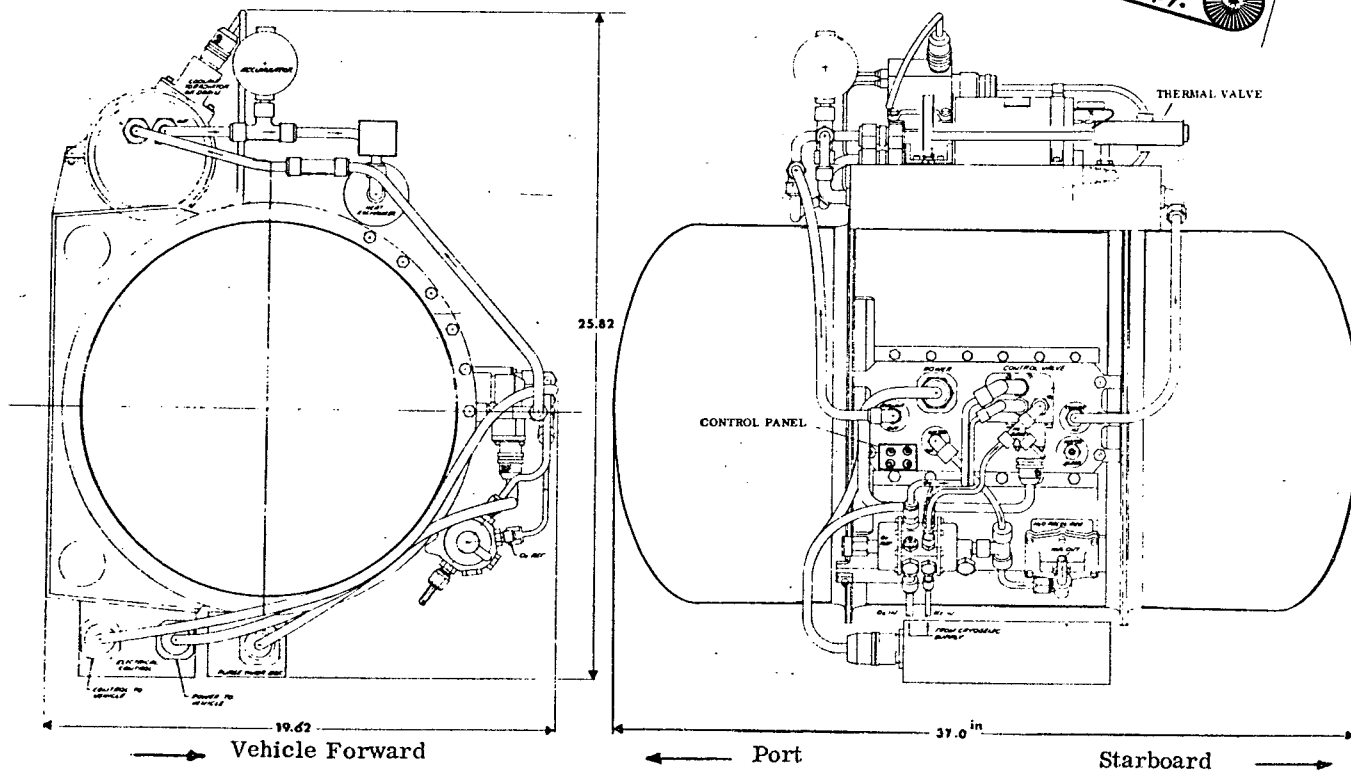


Figure 2. Cross-Section of Back-to-Back Cell Assembly

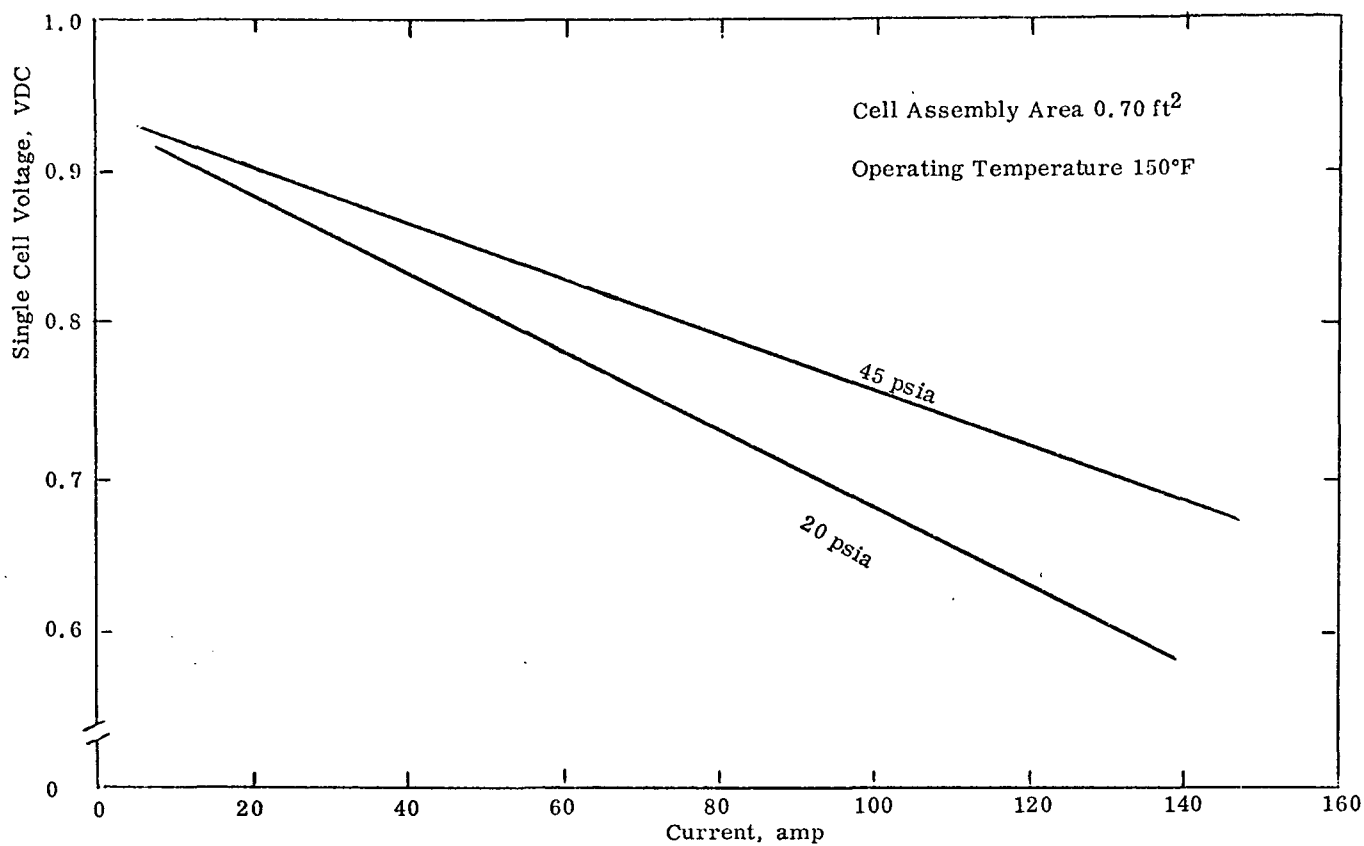


Reproduced from  
best available copy.

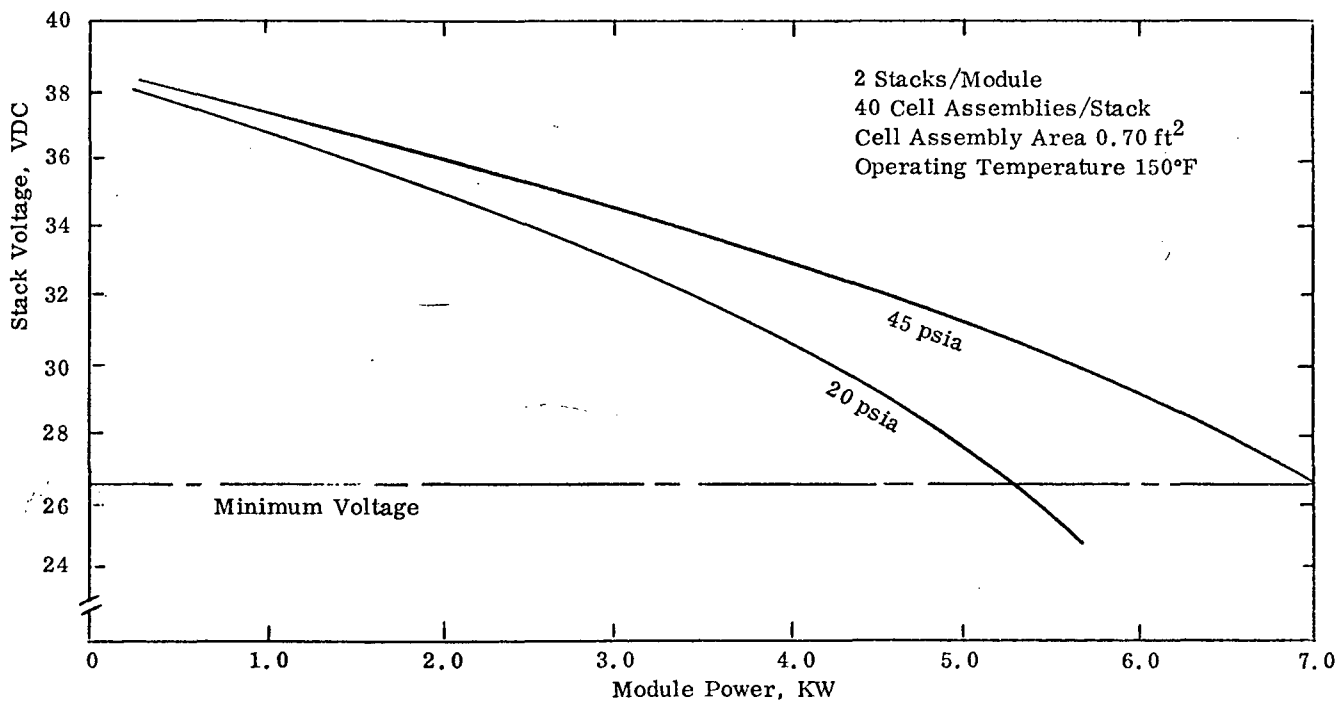


Typical Fuel Cell Module and Ancillary Components Mounting Arrangement

Figure 3.



Single Fuel Cell Performance

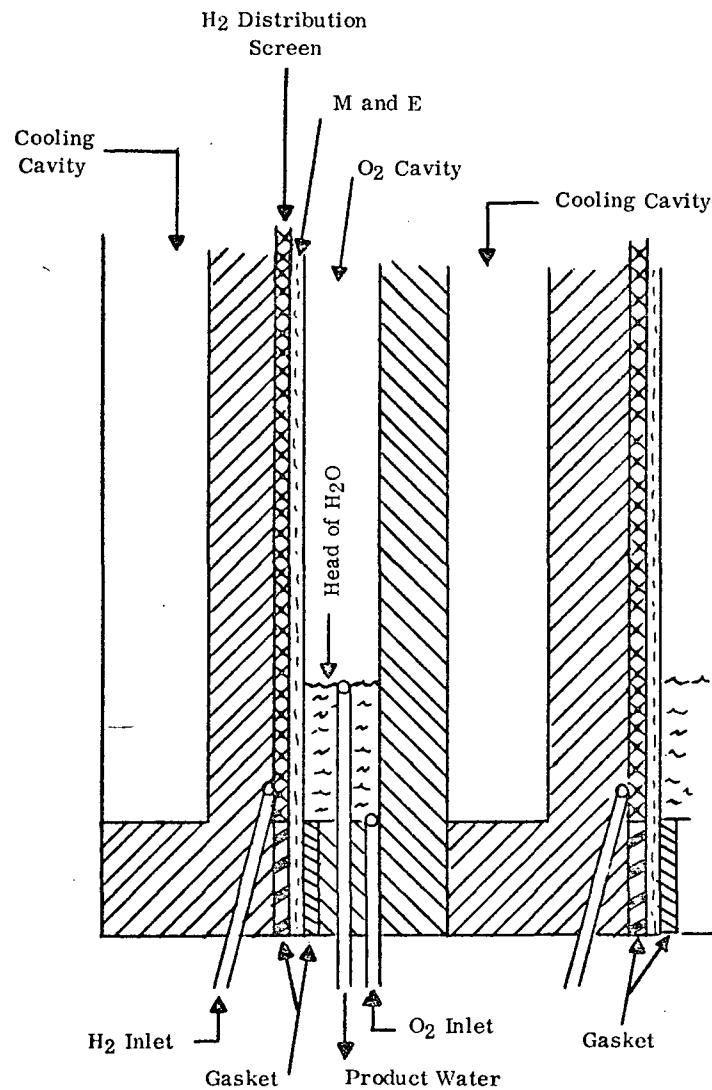


Two-Stack Fuel Cell Module Performance

Figure 4.

### Hardware Comparisons

<u>Characteristic</u>	<u>Space Shuttle Buildups</u>	<u>AFC Units</u>
Polymer	Extruded "R"	Extruded "R"
Anode Catalyst	4-32 mg/cm <sup>2</sup>	4 mg/cm <sup>2</sup>
Cathode Catalyst	4-8 mg/cm <sup>2</sup>	4 mg/cm <sup>2</sup>
Cell Area	51 in. <sup>2</sup>	55 in. <sup>2</sup>
Assembly	Bonded	Gasketed
Container	Pressurized O <sub>2</sub>	Ambient Air
O <sub>2</sub> Feed	50 to 100% Saturated	Internal Water Bubbler
H <sub>2</sub> Feed	Dry Gas	Opposite Head of H <sub>2</sub> O
Load Profile	60 to 135 ASF	Same for 3000 hrs, Double for 1400 hrs
Temperature	150°F	Same for 3000 hrs, 180°F for 1400 hrs
Pressure	20 to 45 psia	70 psia
Wt./Cell Assembly	1 lb	20 lb



Cross-Section of Advanced Fuel Cell Assembly

Figure 5.

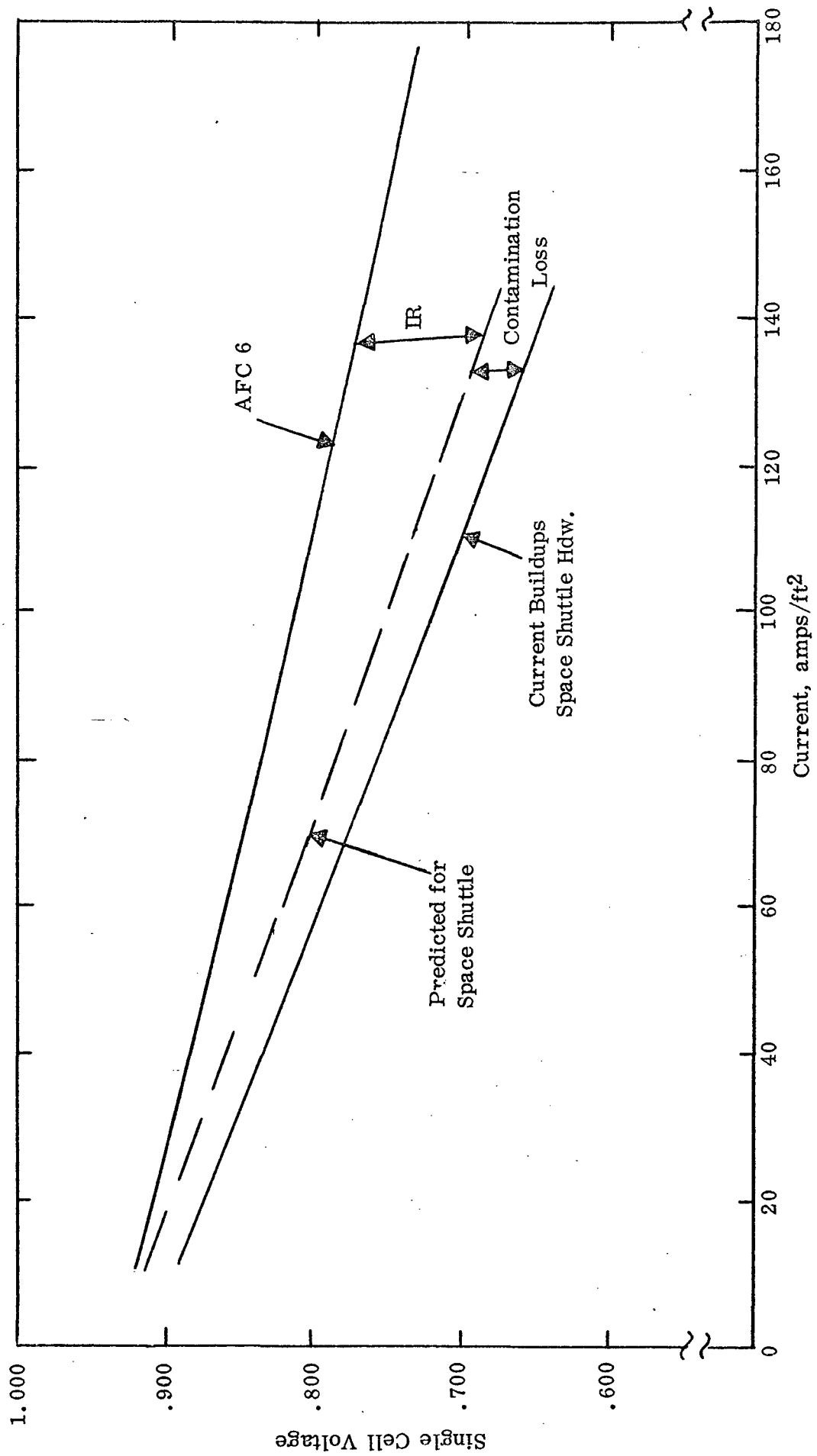


Figure 6. Average Single-Cell Performance Operating at 150°F and 45 psia

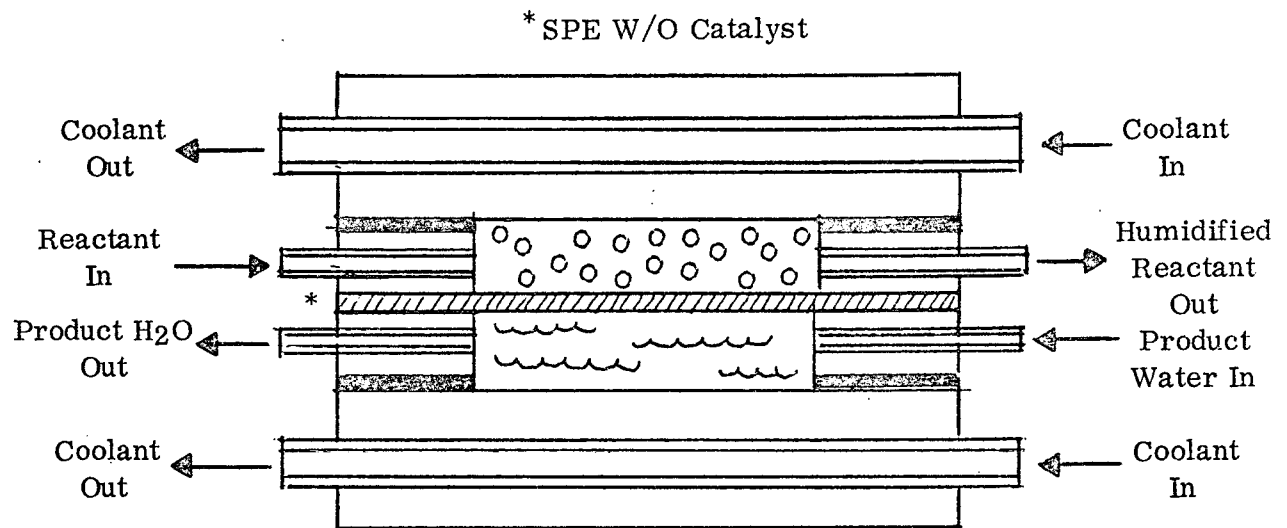


Figure 7. Cross-Section of Reactant Prehumidification Design